

EXPERIMENTAL ATLAS AND AXIS FRACTURES
- A PILOT STUDY

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SUMMARY

Atlas and axis fractures have been produced in impact experiments with cadavers on an acceleration track and in dynamic compression experiments on human cervical spine preparations. The fractures contained many striking similarities to those suffered in real accidents. The results supports the theories that: (1) fractures of the anterior part of the dental arch of the axis is the consequence of antero-flexion of the head with a simultaneous traction or compression of the neck, (2) fracture of the densoid process can be caused by violent antero-flexion of the head in connection with flexion to the upper anterior part of the neck, (3) fractures of the axis arches can be due to displacement and tilting of one of the lateral masses posteriorly-inferiorly.

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SUMMARY

Atlas and axis fractures have been produced in impact experiments with cadavers on an acceleration track and in dynamic compression experiments on human cervical spine preparations. The fractures obtained show striking similarities to those suffered in real accidents. The result supports the theories that: (1) fractures of the anterior part of the neural arch of the axis is the consequence of anteroflexion of the head with simultaneous traction or compression of the neck, (2) fracture of the odontoid process can be caused by violent anteroflexion of the head in connection with impact to the upper anterior part of the neck, (3) fractures of the atlas arches can be due to dislocation and tilting of one of its lateral masses posteriorly-inferiorly.

1. Impact experiments with cadavers on an acceleration track

The purpose of these experiments was to find the design of an instrument panel, which, in case of collision, would offer the car occupant optimal protection. Instrument panels of varying design were used in simulated head-on collision tests in order to give a safe environment for the driver. These experiments were carried out at the Fraunhofer Institut, Dortmund. The experimental equipment has been described in detail by Garmann et al. (1972). Only a brief description will be given: The sled could be accelerated backwards by a gas-hydraulic cylinder motor over a distance of 1 meter with a constant force of 125 kN. After a travel of 2.5 meters the sled was braked to stand still with a deceleration of 7.5 g. In the sled was mounted a conventional car seat. In all 12 uninstrumented uninstrumented cadavers were used in a sitting position on the seat. The instrument panels were provided with chalk marks of different colors which were rubbed off on the clothing of the cadaver during impact. Thus, it was possible to visualize the impact areas of the head and the chest. The movements of the

The present stage of knowledge about the causes of atlas and axis fractures is primarily based on clinical observations and on thorough post mortem investigations correlated to the reconstruction of the course of the events in the accidents. Another way to investigate the genesis of these injuries is to produce them under carefully controlled experimental conditions. Such studies are - because of the specific anatomy of the human neck - only possible on human cadaver material. This study deals with atlas and axis fractures produced experimentally on cadaveric material.

METHODS AND RESULTS

Two different types of experiments were performed: (1) unembalmed human cadavers were subjected to simulated head-on collisions on an acceleration track. (2) A separated part of the base of the skull together with the upper part of the cervical spine with the preserved surrounding soft tissues were subjected to dynamic compression in a mainly longitudinal direction.

1. Impact experiments with cadavers on an acceleration track.

The purpose of these experiments was to find the design of an instrument panel, which, in head-on collisions would offer the car occupant optimal protection. Instrument panels of varying design were used in simulated head-on collision tests in order to give a safe constructional basis. These experiments were carried out at the Max Planck Institut, Dortmund. The experimental equipment has been described in detail by Coermann et al (1972). Only a brief description will be given: The sled could be accelerated backwards by an electrohydraulic catapult piston-rod over a distance of 1 meter with a maximum force of 120 kN. After a free run of 2.5 meters the sled was braked to stand still with a deceleration of 1.3 g. On the sled was mounted a conventional car seat. In all, 32 unrestrained unembalmed cadavers were used in a sitting position on the seat. The instrument panels were provided with chalk marks of different colors which were rubbed off on the clothing of the cadaver during impact. Thus, it was possible to visualize the impact areas of the head and the chest. The movements of the

cadavers were recorded by means of high speed cameras at a rate of 500 pps. One camera was mounted on the sled, another one was stationary beside the acceleration track.

In these experiments bilateral fractures of the neural arch of the axis near the isthmus (hangman's fracture) resulted in one case and a fracture of the odontoid process of the axis in another case.

1.1 Fractures of the neural arch of the axis near the isthmus.

In this experiment the cadaver of a 66-year old man with a height of 167 cm and a weight of 66 kg was used. The terminal velocity of the sled was 57 km/h. The maximum sled acceleration was 25 g. An extremely broad instrument panel was used (see Fig. 1). As seen from the high speed film, the cadaver chin impacted against the upper edge and the knees against the lower part of the panel. The pelvic region was held by the femora on the seat cushion. During the impact the back of the cadaver was bent in a lordosis (hyperextension) with a maximum in the inferior part of the thoracic region. The head anteroфлекed slightly around the impacting chin. The lower part of the neck did not seem to participate in the movement of the head. During the anteroфлекion the parietal region of the head was somewhat elevated in relation to its position in earlier phases of the impact. The trochanter region of the femur (markers sewn to the skin) on the other hand was lowered. This indicates that the whole spine was stretched during the impact (see Fig. 2).

The autopsy of the cadaver revealed fractures of the incisors of the upper and lower jaws. The pia mater was lacerated at the superior margin of both parietal lobes of the cerebrum with surrounding thin subarachnoidal hemorrhages. The axis exhibited a hangman's fracture. The fracture in the left half of the neural arch ran almost vertically through the posterior part of the upper joint surface and the transverse foramen. The fracture of the right half ran obliquely anteriorly-inferiorly, slightly behind the upper joint surface and through the transverse foramen (see Fig. 3). The intervertebral disc between axis and C 3 was lacerated and detached from C 3. Only a small disc fragment attached to the posterior part of the superior surface of C 3

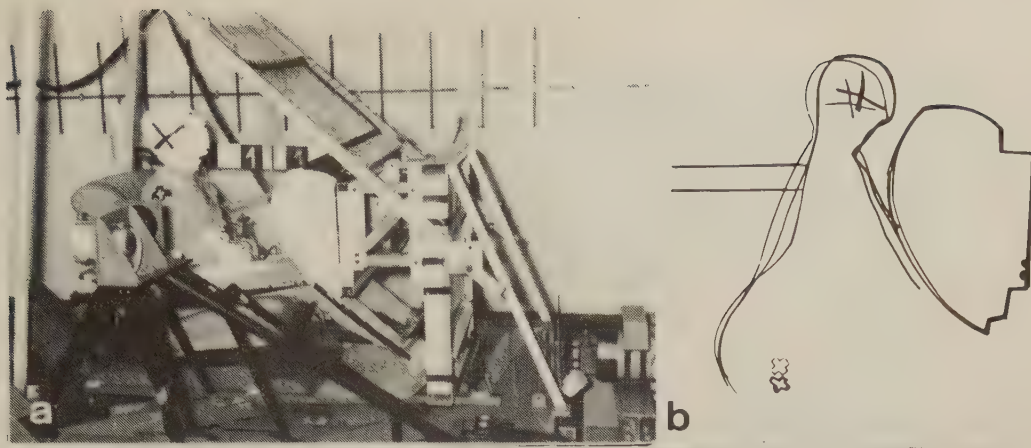


Fig. 1: Impact experiment with a cadaver on an acceleration track.
a) Sled before impact. b) Movement of the cadaver impacting the panel (drawing from high speed film).

Fig. 2: Same case as in Fig. 1.
Movement of a) the center of the mark at the head as seen in Fig. 1 a.
b) Mark at the outside of the axillary joint.
c) Mark in the trochanter region of the femur.
d) Mark at the knee.

Numbers indicate time (msec) from impact (0). Note movement of the head at 43 and 50 msec as indicated by the vertical mark at the head.
Evaluation of high speed film.

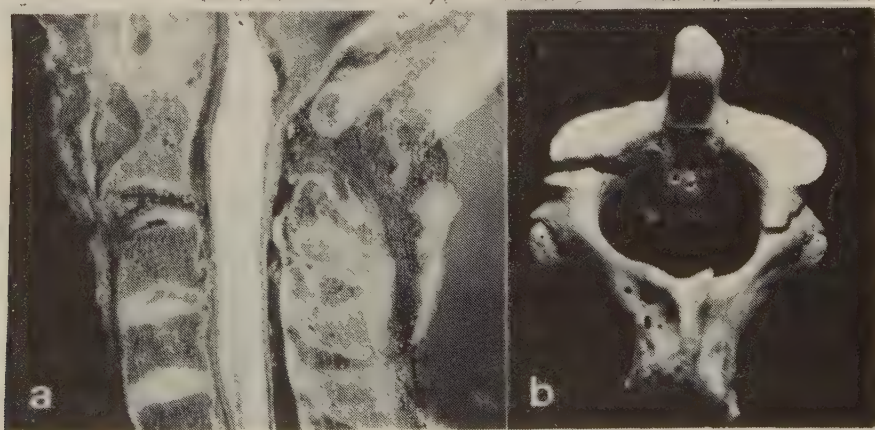
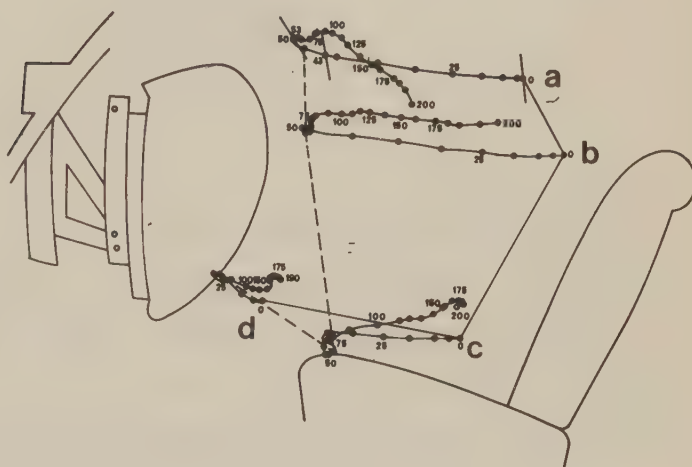


Fig. 3: Same case as in Fig. 1.
a) Soft tissue injuries in the upper part of the cervical spine.
b) Fractures of the axis near the isthmus.

remained. The anterior longitudinal ligament was not lacerated but was detached from the superior region of the vertebral body of C 3. The posterior longitudinal ligament was not ruptured. The odontoid process together with the corpus of the axis could be bent anteriorly due to the lacerations of the surrounding soft tissues. The intervertebral disc between C 3 and C 4 showed small hemorrhages mainly posteriorly. The body of T 10 showed a transverse fracture, gaping anteriorly and the anterior longitudinal ligament was lacerated at the same level. Furthermore, there were multiple rib fractures enabling the lower part of the anterior chest wall to be pressed in with ease.

Thus, the findings strongly imply that the bilateral fractures of the neural arch of the axis (hangman's fracture) is consistent with an anteroflexion of the head in combination with a longitudinal traction of the neck.

1.2 Fracture of the odontoid process.

The instrument panel in this experiment was designed to absorb energy by deformation when impacted by the anterior thoracic wall. Thus, the panel was constructed to fold downward rather than upward to prevent neck and head contact with the upper edge of the panel. In this experiment the instrument panel malfunctioned and folded upward as well (see Fig. 4).

The cadaver of a 55-year old man with a height of 184 cm and a weight of 71 kg was used. The terminal velocity was 45 km/h and the maximum acceleration of the sled was 24 g. The high speed films showed that the neck struck a portion of the instrument panel which had folded upward and the chalk mark situated at the highest part of the deformed panel was rubbed off on an area 1 cm above the larynx. The head of the cadaver wore a helmet equipped with accelerometers. Unfortunately, the helmet, which was not properly secured, rotated anteriorly and concealed the head from the cameras. Thus, it was not possible to determine the exact movements of the head from the high speed films. However, the chalk mark on the upper surface of the panel had been transferred to the anterior side of

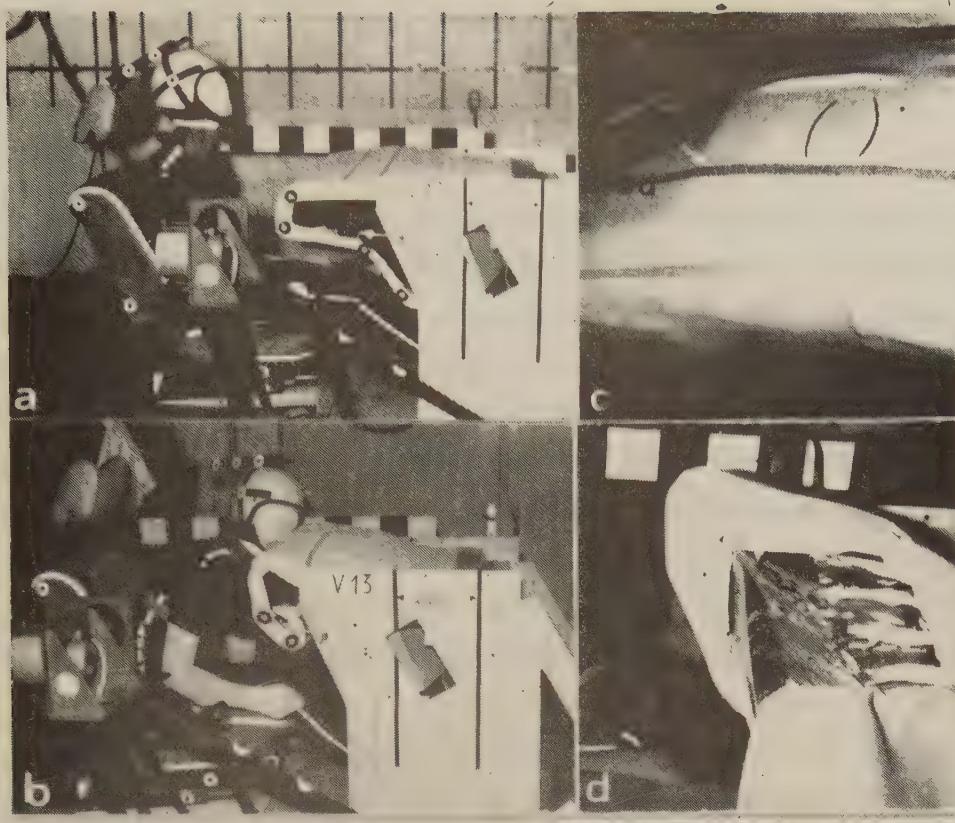


Fig. 4: Impact experiment with a cadaver on an acceleration track.
 a) Sled before impact. b) Sled after impact. Note deformation of the panel. c) Panel after impact. Marks indicate the head impact area (softening of the plastic foam). d) Panel after removing plastic foam layer. Note upward folding of the metal sheet.

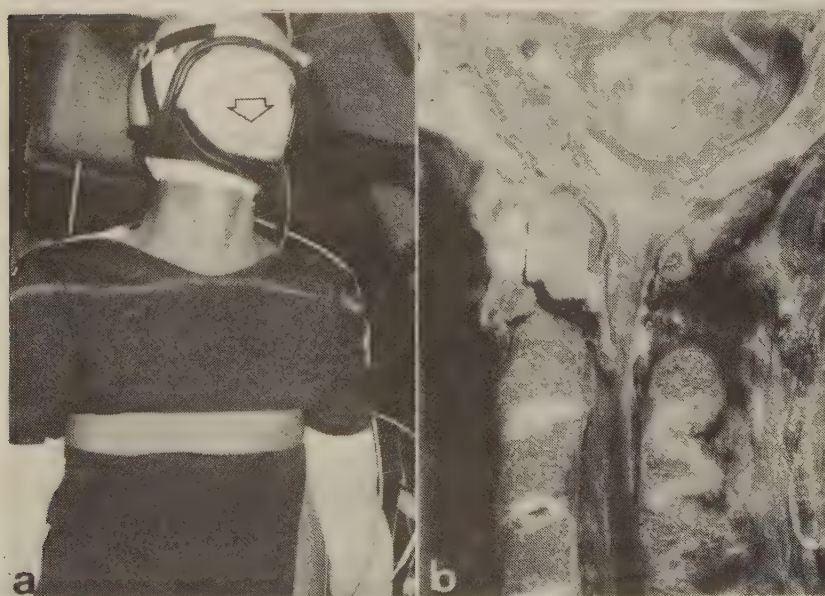


Fig. 5: Same case as in Fig. 4.
 a) Chalk mark at the anterior side of the chin (red chalk).
 b) Fracture of the odontoid process of the axis.

the chin (see Fig. 5). Thus, it could be concluded, that the head had anteroflexed about 90° .

The autopsy revealed disruption of several bridging veins with small surrounding subarachnoidal hemorrhages at the superior margin of the cerebrum. The odontoid process of the axis together with the medial parts of the superior joints and the superior part of the body had been broken off and a small fragment at the anterior side of this fracture was separated. Both the anterior and posterior longitudinal ligaments were ruptured at the level of the fracture. The intervertebral disc between the axis and C 3 was intact. There were hemorrhages in the muscles between the posterior arch of the atlas and the neural arch of the axis. The odontoid process could easily be bent anteriorly, due to the injuries to the surrounding soft tissues. The hyoid bone was fractured.

Thus, according to the results of this experiment, the fracture of the odontoid process is consistent with a violent anteroflexion of the head.

2. Compression experiments.

The preparation used in the compression experiments consisted of the bony structures surrounding the foramen magnum (parts of the occipital, temporal and sphenoidal bones), the first, second and third cervical vertebra and the surrounding soft tissues (muscles, ligaments and joint capsules). Care was taken so that muscle and ligament insertions were preserved undamaged. The upper and lower ends of the preparation were as far as possible sawn horizontally, parallel to each other. The preparations were subjected to dynamic compression in a longitudinal direction. The force history was recorded by means of a piezoelectric transducer.

2.1 Peak force: 320 kp. Impact velocity 3 m/s.

The part of the base of the skull included in the preparation was flattened by the compression and showed several fractures extending in various directions. Due to the fractures both condyles rotated around a sagittal axis.

The atlas sustained bilateral, almost vertical fractures in both the anterior and the posterior arch. Both the inferior joints showed impressions. The transverse ligament of the atlas was lacerated on the left side. Thus, the preserved parts of the base of the skull had been flattened and the lateral masses of the atlas had been displaced in lateral directions.

The neural arch of the axis had bilateral transverse fractures running through the posterior part of the superior joint surfaces and the foramina transversaria. Furthermore, there was a comminute fracture of the inferior part of the corpus. Due to the lacerations of the surrounding soft tissues the bilateral fractures of the neural arch were gaping superiorly and the corpus together with the odontoid process of the axis had been forced somewhat inferiorly (see Fig. 6). Thus, it seems reasonable to assume that these fractures were the result of an anteroflexion of the anterior part of the axis, combined with a compression of the vertebra.

2.2 Peak force: 200 kp. Impact velocity 2 m/s.

The saw cut through the third vertical vertebra was somewhat oblique. Therefore, the impact mainly resulted in a compression of the right posterior part of the preparation.

The part of the base of the skull included in the preparation exhibited a fracture running from the right side of the foramen magnum to the right, a fracture extending from the left side of the foramen to the left, and a fracture from the right posterior part of the foramen running posteriorly. The part of the skull base in the preparation thus had been flattened.

The anterior arch of the atlas showed a widely gaping vertical fracture at the junction of the anterior arch and the right lateral mass and another fracture immediately to the left of the facet for the odontoid process running from right superiorly to left inferiorly. Around this fracture the soft tissues were not lacerated. The soft tissues were detached from the anterior side of the atlas to the right of the right fracture of the

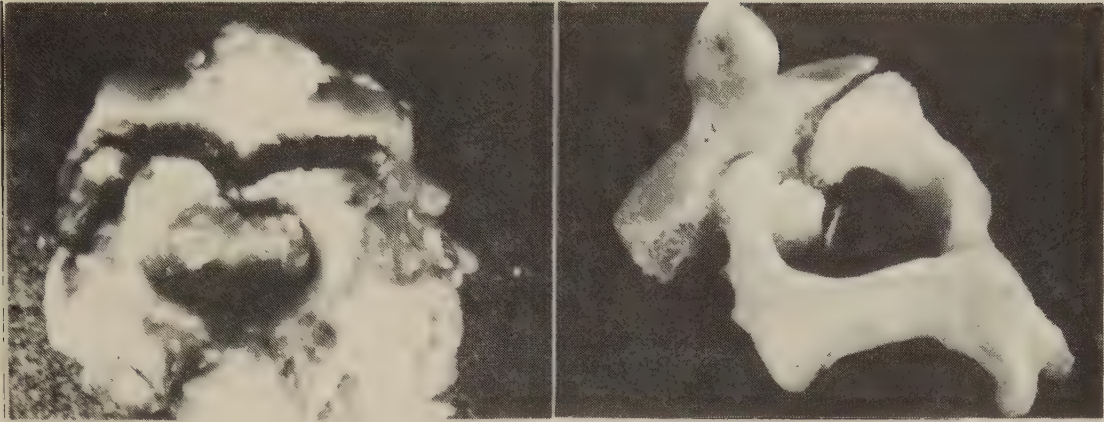


Fig. 6: Compression experiment. Fractures of the neural arch of the axis, before and after removal of the soft tissues.

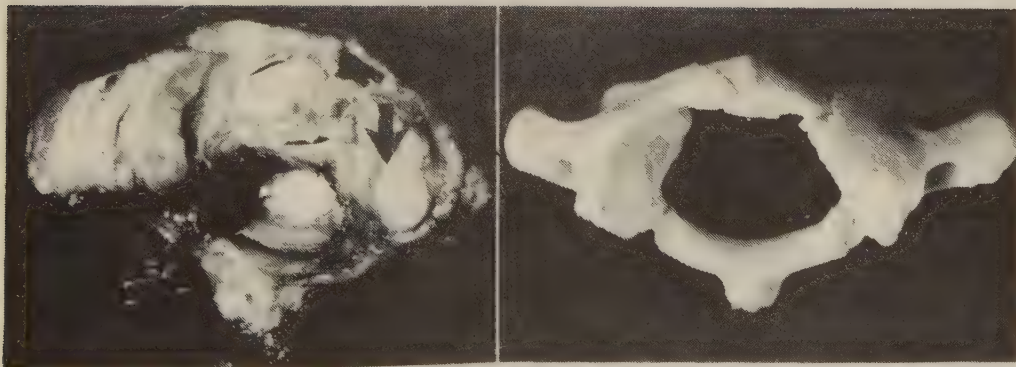


Fig. 7: Compression experiment. Atlas fractures before and after removal of the soft tissues. Arrow indicates dislocation of the right lateral mass of the axis.

anterior arch. Furthermore, there were bilateral fractures of the posterior arch in the regions of the grooves for the vertebral arteries.

The axis showed bilateral fractures of the neural arch posterior to the inferior apophyseal joints gaping inferiorly.

According to the soft tissue injuries the right lateral mass of the atlas had been dislocated inferiorly and posteriorly (see Fig. 7). This movement was reasonably counteracted by the odontoid process of the axis producing the fractures of the anterior arch. The right part of the posterior arch of the atlas was forced inferiorly and the left part of the posterior arch levered superiorly about the posterior part of the axis. The fractures of the neural arch of the axis can be explained by a direct pressure from below.

2.3 Peak force: 120 kp. Impact velocity 2 m/s.

In this case the skull base preparation showed a transverse fracture running in front of the condyles. Furthermore, there was a fracture in the midline of the corpus of the occiput and fractures of the squama occipitale. The fractures of the base of the skull were due to flattening.

The atlas and axis were not injured.

DISCUSSION

Fractures of the atlas and axis are almost always the consequence of violent movement of the head in relation to the trunk, usually because of direct trauma to the head. Sköld (1977, 1978) has recently studied the genesis of fractures of the arches of the atlas and of the odontoid process and neural arch of the axis in persons killed in accidents, mostly car occupants. His concepts of the deformation of the neck causing the fractures were based on thorough investigation of the cervical spine, especially the soft tissue injuries around the fractures, and close reconstruction of the course of events in the accidents. It is obviously of great value to compare such interpretations with the result of investigations, in which fractures of the same type have been produced experimentally, i.e. when relevant physical parameters (force, movement, velocity etc.) can be recorded.

Contrary to general opinion Sköld (1977) has claimed that fractures of the anterior part of the neural arch of the axis (hangman's fracture) are usually due to anteroflexion of the head and that simultaneous traction or compression of the neck seems to be of significant importance. In those cases in his material where the anteroflexion of the head was due to its inertia after impact against the lower part of the face a simultaneous traction of the neck was at hand. The same type of traumatic situation occurred in the cadaver experiment in which bilateral fractures of the neural arch of the axis was obtained and these fractures had the same appearance as those seen in accident victims. The asymmetry of the fractures may be explained by an anteroflexion of the head in a slightly oblique direction (which in this case could not be determined from the high speed films since they were taken from the side). Small bilateral differences in the strength of the bones and of the soft tissues between the skull and cervical spine may also be responsible for the asymmetric location of the fractures.

The fracture of the odontoid process in one experiment (1.2) was reasonably the consequence of a violent anteroflexion of the head probably around the impacting upper part of the anterior side of the neck. Fracture of the

odontoid process of the same appearance and genesis has been observed by Sköld (1977) in an accident victim. It cannot be excluded, however, that the fracture in the experiment was promoted by the impact of the face against the upper side of the panel after anteroflexion of the head (Sköld, 1977) despite the coating of the surface of the panel with a thick layer of energy absorbing plastic foam.

There were obvious dissimilarities between the events in the compression experiments and the events in actual accidents. In accidents the compression forces always are transmitted by the head to the atlas and axis (e.g. impact against the vertex of the head or the inertial effect of the head, when the victim in an upright position after a jump from a height lands on his buttocks or feet). In the present experiments only a part of the base of the skull could be preserved and in all three cases did not withstand the impact against the sawn border of the preparation. Thus, the preserved part of the base of the skull had been flattened with resulting fractures. In the first compression experiment the impact resulted in a hangman's fracture and in compression fractures of the inferior part of the body of the axis. The observations in this experiment strongly support Sköld's theory concerning hangman's fracture due to anteroflexion of the head combined with longitudinal compression. Concerning the atlas, bilateral fractures of the anterior and posterior arch resulted. These fractures may be due to a deformation transmitted by the dislocating fracture fragments of the occipital bone (lateral bending of the lateral masses of the atlas) but the fractures of the anterior arch may also be the consequence of an impact of the anterior border of the foramen magnum.

In the second compression experiment with lower force the surface of the third cervical vertebra was sawn in such a way that the compression of the cervical spine mainly acted in its right posterior part. In this case the atlas fractures were due to a displacement of the right lateral mass of the atlas in posterior-inferior direction against the resistance of the odontoid process and the posterior part of the axis. Similar findings have been made by Sköld (1978) in his investigation of the genesis of atlas fractures in accident victims.

The compressive properties of the human vertebra were investigated by Sonoda (1962). The compressive breaking load of wet cervical vertebrae was found to be age dependent:

337 ± 9 kg for the age group 40-59 years and

190 ± 6 kg for the age group 60-79 years

The result of the present three preliminary compression experiments agree with these data concerning the order of magnitude of the breaking load. However, further tests have to be made in order to establish the possible fracture patterns of the cervical spine in compressive load with the preparation straight, flexed, hyperextended or rotated (cf. Gosch et al, 1972).

One comment should be made about the duration of the force action in the experiments. It is known that ultimate strain or stress of bone is fairly insensitive to change in the strain rate (cf. Wood, 1970). Nevertheless, efforts should be made to use force action durations which are comparable to accident situations. The pulse duration used were about 20-30 msec. This force action duration is somewhat longer than in actual situations (5-10 msec) but it is not felt that any importance should be attached to this difference. The important fact is that the natural period of the vertebrae is much short and, therefore, the duration of the force action will not influence the load bearing capabilities of the cervical spine.

The results of investigations on cadaveric material may be influenced by post mortal changes of the mechanical properties of the different tissues involved and by the loss of muscular tone.

Compared to normal muscle tone, a paralyzed or a tetanic state of the neck muscles gives a somewhat higher head displacement amplitude in the living baboon subjected to experimental head-on collision tests (Martin et al, 1974). In the present cadaver experiments rigor mortis had disappeared and no muscle tone was present.

Concerning compression of the neck Gosch et al (1972) report that the state of muscle tone of the neck in the monkey (*makacca mulatta*) has a notable influence on the ability to produce cervical spine injury and in their experiments cervical spine injury occurred at lower force levels when muscle tone was present. Rigor mortis was to some extent present in the cervical spine preparations used in the present compression experiments.

Possible influence of the above-mentioned effects of muscle tone cannot be sufficiently estimated. With relation to the present experiments, however, it seems reasonable to assume that the main effect of missing muscle tone in the full-scale cadaver experiments and the rigor mortis state of the muscles in the compression experiments is to change tolerance levels for injury and not the genesis. Furthermore, it is hazardous to relate animal experiment results to human cervical spine injuries because of anatomic features.

The findings in these experiments display evident similarities with Sköld's (1977, 1978) interpretation of cervical spine injuries in accident victims. The results of the present investigation therefore support his opinion concerning the genesis of fractures of the arches of the atlas and of the odontoid process and neural arch of the axis.

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